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METABOLIC MECHANISMS OF MAN IN THE FULL PRESSURE SUIT

Physiological Cost of Donning a Full Pressure Suit

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ADMINISTRATIVE INFORMATION

Foundational Research Project #32 entitled "Metabolic Mechanisms of Man in the Full Pressure Suit" was approved by the Naval Air Engineering Center Foundational Research Board, and funding was provided on 25 October 1963 by authority of WEPTASK R360FR 101/200-1/R011 0101. Construction of a suitable test facility with associated instrumentation is currently underway. The present report represents work accomplished while waiting for the primary test facility to be completed. Some of the data included here was presented before the American Physiological Society during the Annual Meeting of the Federation of American Societies for Experimental Biology on 15-17 April 1964. The contents of the present report will be published in the proceedings of a "Symposium on Spacesuits and Human Performance," sponsored by the Society of Engineering Psychologists, American Psychological Association.

ABSTRACT

Experienced subjects donned the U.S. Navy MK-4 Full Pressure Suit under conditions of time and donning space limitations. Direct and indirect measures of physiological cost were made using oxygen consumption and heart rate, respectively. Approximately 1 kcal of energy per kg of body weight was expended in the donning task. Donning volumes as small as about 7 times the volume of the subject's body accommodated the dressing procedure with no apparent increases in donning time nor in energy expenditure. Suit fit was found to have an important effect on both effort and time required for donning.

The purpose of this report is to describe some tests which were conducted in an attempt to identify and quantitatively evaluate the physiological cost of donning a full pressure suit under space and time limitations. From the operational viewpoint, this matter is of importance to manned space flight, where factors relating to suit donning include pressure suit design and evaluation, accommodations in the limited living compartments of space craft for dressing and suit stowage, and provision of gaseous and nutrient supplies for accomplishing work tasks, including the donning procedure. In view of proposed "shirtsleeve" conditions for future space flights, accidental decompression of the space capsule makes all factors relating to pressure suit donning of critical importance for space crew survival.

In addition to these operational aspects, the donning of a full pressure suit offers an opportunity to evaluate human performance in the accomplishment of a non-repetitive, complicated physical task. While the literature abounds with studies of the physiological cost of performing work tasks involving a limited part of the body and repetition of relatively simple, cyclic movements, little data exist for the case of complex activities made up of transient work sequences. The more usual measures of performance, such as number of errors made, or reaction time, give no indication of the physiological effort required, yet the latter may play the most crucial role in task accomplishment.

METHOD

Since donning the pressure suit involves the capability of executing rather extensive bodily movements, as well as pulling a helmet over the head, measurement of oxygen consumption by a hose leading to the subject's mouth was not possible. Instead, energy expenditure was calculated from continuous measures of heart rate, and, in some cases, from gas analyses made while having the subjects dress in an impermeable bag of known volume.

Three naval enlisted men (designated B, C, and M) served as subjects for those tests in which estimates of donning work were obtained from measures of heart rate. One of these subjects, C, and an additional naval enlisted subject, CM, participated in those tests where oxygen consumption was measured directly in the impermeable bag. All of the subjects were well experienced in the suit donning procedure, having spent years as subjects in various kinds of tests involving use of the full pressure suit. Additional practice in suit donning was given prior to the tests described here. Various anthropometric data on these subjects is shown in Table 1.

All tests were conducted at sea level pressures and room temperatures. A commercially available radioelectrocardiographic system (manufactured by Telemedics Inc., Southampton, Pa.) was used to obtain recordings of heart rate. ECG signals from electrodes fixed to the torso were led to a small transmitter strapped to the subject's waist, and, from there, were broadcast to a nearby receiver and stripchart recorder. Analyses of gas samples were made using a standard Scholander microgasometer. Pre- and post-test oral temperatures and body weight were measured initially, but could not be related in any systematic way with the test conditions nor the work performed, and therefore these measurements were subsequently omitted.

Each of the subjects was "calibrated" for various work loads on a treadmill by measuring oxygen consumption directly, and simultaneously obtaining a continuous record of heart rate. An initial 30 minute rest period was followed by a 2 minute control period, a 6 minute work period, and a 5 minute recovery period. Previous experience had indicated that the subjects required approximately 6 minutes to don the full pressure suit. The rate of oxygen utilization for performing treadmill work was calculated by subtracting resting oxygen consumption for the duration of the recovery period from the total oxygen used during the work and recovery periods, and dividing this difference by the duration of the work period, namely, 6 minutes. In an analogous manner, average heart rate during the work period was calculated by subtracting resting heart beats for the duration of the recovery period from the total number of heart beats during the work and recovery periods, and dividing this difference by the duration of the work period, again, 6 minutes. In a number of runs, steady state values of oxygen utilization rate and heart rate were attained in 4 to 6 minutes of treadmill work, and these values were found to be the same (within the limits of experimental error) as those calculated in the manner just described. Table 2 shows a comparison of steady state and calculated average heart rate during treadmill work for two subjects. The "calibration" curves relating work rate (using the caloric value of 5 kcal per liter of oxygen) to heart rate for each of the three subjects used in this study are shown in Fig. 1.

Before donning the U.S. Navy MK-4 full pressure suit, the subject dressed in long, cotton underwear and thin socks. He was instructed to dress as quickly as possible after control values of heart rate were determined. Each subject donned the pressure suit in his own manner, although all gross movements and manipulations were essentially similar among subjects and among tests. As shown in Fig. 2, the dressing sequence began and ended with the subject seated. After the feet and legs were inserted, and the boots put on, the subject stood and pulled the suit over his hips. The arms and upper torso were inserted through the large zippered entrance running diagonally across the suit front. The waist zipper was opened to allow for extension of the suit as the neck ring was pulled over the head. Waist and diagonal front zippers were then closed, and the subject sat down. After the helmet was donned, the gloves were put on, zippered to the arm sections, two small zippers in the neck area were closed, and the helmet visor lowered. Completion of this last action signalled the end of the dressing task.

In order to change the donning volume in a controlled fashion, the apparatus shown in Fig. 3 was used. It consisted essentially of a metal framework supporting a number of flat, transparent acrylic panels. The shape and volume of the contained dressing space was changed by adjusting these panels. The enclosed volume was calculated by summing volumes of regular shapes into which the total had been divided for analytical purposes. The volume of a chair, included to provide support during the initial and final phases of the donning procedure, as well as the space behind and under it, was excluded in calculating dressing volume. Subjects were instructed not to lean against the panels for support during the dressing procedure.

In order to obtain a more direct measurement of work during donning, each of two subjects dressed themselves while enclosed within a gas-tight, flexible

bag, suspended so that its bottom rested on the floor. The bag was cylindrical in shape, with a diameter of about 3 ft. and a length of about 6 ft. An outer nylon fabric layer covered an inner, rubber lining; the top and bottom of the cylinder were composed of heavy, rigid, circular plastic plates. A heavy-duty, pressure-sealing zipper closed the bag entrance (Fig. 4). To allow the dressing procedure to be carried out as already described, a small stool was located within the bag. The interior of the bag was lighted by a small electric bulb located in its upper portion.

Because of the flexibility and irregularity of its walls, bag volume was estimated by the gas dilution technic. Ten liters of pure oxygen were introduced into the bag through an access tube. The bag contents were then mixed by vigorous movements of its walls. Samples of mixed gas were withdrawn and analyzed to determine their oxygen content. From the proportion of oxygen in the mixed gas sample, the volume of the bag was readily calculated. Twenty such estimates yielded a mean bag volume of 1265 liters, with a standard error of 16.9 liters.

Before entering the bag, each of the subjects was given a 30 minute rest period. Meanwhile, the air in the bag was thoroughly mixed and a sample taken for analysis. After entering the bag, the zipper was closed and the subject immediately started to dress in the pressure suit, which had been previously stowed inside. The sides of the bag were vigorously moved to and fro by an observer to mix the gases within. Completion of the dressing task was signalled by the subject, who then sat quietly at rest for an additional 10 minutes. Gas samples were withdrawn at 5 and 10 minutes during the recovery period. In order to guage the effect of suit size on the work of dressing, each of the subjects donned a tight-fitting suit for his last test.

RESULTS

Measurements on the physiological cost of donning the full pressure suit in a limited space are shown in Table 3. It was found that the donning volume could be reduced to the point of grossly limiting limb and body movements before any appreciable effect on donning time or effort expended could be measured. This is illustrated in Fig. 5, where the total work of dressing per unit body weight is plotted against volume ratio. Volume ratio represents the ratio of donning volume to the volume of the subject. The latter was calculated by assuming a mean body density of 1.067 kg per liter. Subjects are indicated in Fig. 5 with their symbols in order of decreasing size. The largest subject, M, expended more energy in dressing at the various volume ratios than did either of the other two subjects. M's very high energy expenditure at the smallest volume ratio may partially reflect the cumulative effects of a previous test from which he may not have fully recovered. Volume ratios below 7 were so restrictive as to physically prevent the subjects from making the movements required to dress.

Distribution of work done during a typical dressing and recovery sequence is shown in Fig. 6 as a solid line for one of the subjects. Work periods on the treadmill at different work rate levels which bracket the work rate of dressing are shown as dashed lines. As already stated, steady state values of

work rate had been firmly established on the treadmill by the sixth minute, and therefore this rate is continued at the same level to the beginning of the recovery period. Approximately 27 per cent of the total work of dressing was expended in getting the upper torso and arms into the suit, pulling the neck ring over the head, and closing the diagonal entrance zipper.

Table 4 summarizes the data obtained from those suit-donning trials made in the gas-tight bag. In order to indicate the difference in donning cost due to suit fit, the mean for those trials conducted with moderately tight-fitting suits is calculated separately from that in which the suit fit tightly. It can be seen that in the case of donning a tight-fitting suit, donning time increased over 20 per cent, while the total work required to perform the task increased over 40 per cent. When heart rate and oxygen consumption were measured simultaneously while the subject dressed in the bag, the mean work estimate deduced from heart rate was approximately 10 per cent greater than that based upon oxygen used (Table 5).

Benedict measured energy expenditure directly in a respiration calorimeter, and classified muscular work as follows: 2.83 kcal per min. - light; 4.84 kcal per min. - moderately active; 7.5 kcal per min. - severe; and 10.0 kcal per min. - very severe (1). On this basis, the donning task studied here was equivalent to "severe" or "very severe" muscular work, depending upon the subject. This level of work is similar to that found by measuring oxygen consumption during donning of a pressure suit by altitude acclimated subjects confined in a low pressure chamber (14,000 to 20,000 ft. altitude equivalent) for a prolonged period (7).

DISCUSSION

The relationship of heart rate to exercise has been extensively studied, and many workers have demonstrated that for work loads within the subject's aerobic capability, at moderate temperatures, heart rate is linearly related to oxygen consumption (2, 5, 6, 8, 9).

Recently, Poulsen and Asmusser (10) used telemetered heart rate to evaluate energy requirements of various jobs performed by handicapped persons having limited work capacity. Streimer and his associates (12) evaluated the work done by subjects wearing pressure suits, in normal and reduced traction environments, by measuring heart rate. Therefore, the principle of the method employed in the study reported here is believed to be well validated.

The task described in the present study is rather unusual for several reasons. In the first place, it is not, in reality, a single task, but a succession of subtasks, varying both in intensity and duration, and separated from each other by periods of irregular duration. Recovery from a particular, strenuous subtask may therefore proceed during periods of reduced activity occurring in less strenuous subtasks or rest intervals. In addition, almost all skeletal muscles of the body become involved, at one time or another, in the performance of the donning task. It is well known that tasks requiring only the arms are performed less efficiently (from the standpoint of work output to energy used) than those using the legs (10). Furthermore, even with the same part of the body primarily

responsible for doing work, certain work rates are more efficient than others. Thus, cycling at 70 rpm is about 22 per cent efficient, while treadmill walking at 3.5 mph, or cycling at 20 or 170 rpm, are only 15 per cent efficient (3). Finally, as the subject envelopes his body with the suit, he changes both his microclimate and his mechanical environment. These changes tend to make the work task of dressing even more difficult, since the changes are in the direction of impeding body heat loss and increasing mechanical resistance to movement.

The mechanical efficiency of the donning task cannot be evaluated because there is no way of measuring the physical work accomplished. The task itself involves elements of lifting, lowering, pulling, pushing, sitting, standing, twisting, stepping, and other movements even more difficult to classify. Each subject, while attempting to dress in the shortest time consistent with his own characteristics of body size, muscular coordination, and motivation introduced variations in accomplishing the task which were not only different from those of the other subjects, but were also changed to some extent, from one of his own trials to the next.

Of course, a so-called "steady state" cannot be achieved in performing a task such as the one described in this report. Yet some index of heart rate must be used to relate work done during donning to that accomplished in the calibration test of treadmill walking. For this reason, the correspondence shown in Table 2 between average heart rate and steady state heart rate is important. The assumption made here, in ascribing certain equivalent oxygen utilization values to the donning task trials, is that, like the case for treadmill walking, there is a corresponding steady state heart rate which is equivalent to the calculated time-average heart rate. The resting heart rate during the recovery period is eliminated in determining the average heart rate during the work period, since it obviously contributes nothing with respect to the total work performed.

Although no studies were made on donning shape variation, it is evident that in addition to sufficient volume, the shape of this volume is also important. In general, it would appear desirable that the subject have available a roughly cylindrical volume to dress in, with its long axis parallel to the long axis of his body. The orientation of this axis with respect to the surround would appear to be of little or no importance under weightless conditions; if a gravitational field were available, it would appear desirable, in view of man's past experience, to have him and the donning space oriented with respect to this field as they were in this study. It is conceivable that under weightless conditions, the parts of the suit could be positioned conveniently in space in such relation to each other that relatively simple thrusting motions could be made to don one part after the other. However, the inadvertent displacement of a suit part under these conditions could result in a three-dimensional search which would not only be time consuming, but also would require the expenditure of considerable effort. By repeatedly flying parabolic maneuvers, a series of weightless intervals were recently created in a JC-131B aircraft. During these intervals, a subject donned and doffed a prototype APOLLO pressure suit (11). The donning procedure consumed a total of between $2\frac{1}{2}$ and 3 min., and seemed to show that even under highly artificial experimental conditions, no major problems in dressing were encountered. Heart rate was not measured in these experiments.

The energy cost of donning the MK-4 suit as determined by the pulse rate averaged 0.990 kcal/kg for 24 trials, and 0.942 kcal/kg for the 7 dressings in the bag, where oxygen used was measured directly. In view of the many variables involved in a study of this kind, this agreement is indeed remarkable. In fact, if the performance of the one subject (C) exposed to both constrained volume and bag trials is examined, it can be calculated that mean work per kg of body weight is lowest when derived from oxygen consumed in the bag, next lowest when derived from heart rate in the constrained volume, and highest when derived from heart rate in the bag. While these estimates of mean work are not statistically different because of the large variations under all conditions, it is believed that the high values based on pulse rate measured in the bag may reflect the added stress of heat. A temperature rise of the ambient air within the bag of about 5°C occurred from the beginning of the dressing sequence to the end of the recovery period - about 17 min. As pointed out by Brouha and his associates, heart rate during exercise is fairly sensitive to environmental temperature changes, while oxygen consumption remains essentially unaffected by the added temperature stress (4).

Although the data are scanty, there is a clear indication that suit fit plays a critical role in determining the amount of energy used in dressing, and this is substantiated on the basis of casual observation of many subjects donning pressure suits over a period of many years. Unfortunately, suit fit defies any kind of quantitative evaluation. Aside from some general adjectives, such as "tight" or "loose," no objective way has yet been found to precisely describe how clothing fits the wearer. Perhaps a measure of the energy change required to perform a series of tasks with suits of various fit, both pressurized and unpressurized, would provide a useful and pertinent solution to this problem.

Another profitable approach to the problem of objectively measuring aspects of complex physical tasks involves the use of a "force platform." Brouha has described such a platform which incorporates piezo-quartz crystals to measure forces in three orthogonal planes (5). Forces generated by a working subject supported by the platform are presented for analysis in the form of force-time records. These in turn can be interpreted in terms of efficiency in carrying out tasks which involve complicated body movements made up of many transients. Use of this device could also provide additional information on the factor of suit fit and its relation to the donning task.

While the few kinds of pressure suits presently in existence are all somewhat similar in design and construction, it is certain that radical changes will be forthcoming as engineers attempt to meet an increasing variety of requirements in a more efficient manner. For example, in place of the present fabric and rubber suits, which remain soft and flexible until pressurized, prototypes of "hard-shell" suits have been constructed of metal. In order to evaluate the physiological cost of donning suits which are appreciably different from those used in the present study, it is obvious that further testing is necessary. With sufficient refinement of procedures and measuring equipment, it is conceivable that even small segments of the donning task will lend themselves to being evaluated separately, thus providing valuable guidance to pressure suit designers.

CONCLUSIONS

1. Experienced subjects expended approximately 1 kcal of energy per kg of body weight in donning the U.S. Navy MK-4 full pressure suit under the test conditions.

2. Donning volumes as small as about 7 times the volume of the subject's body accommodated the dressing procedure with no apparent increases in donning time nor in energy expenditure.

3. Suit fit had an important effect on both effort and time required for donning.

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TABLE I

ANTHROPOMETRIC DATA OF SUBJECTS

Subj.	Height		Sitting Height		Shoulder Breadth		Buttock-knee Length		Buttock-leg Length	
	Inches	%ile	Inches	%ile	Inches	%ile	Inches	%ile	Inches	%ile
M	70.9	63	37.4	84	20.7	99	23.6	55	43.9	72
B	70.3	50	37.5	85	19.4	96	23.0	38	44.3	76
C	66.3	4	35.5	38	17.8	55	22.1	17	41.0	29
CM	68.9	29	35.6	40	17.4	35	24.3	75	43.0	59

TABLE 2

COMPARISON OF STEADY STATE AND AVERAGE HEART RATE MEASUREMENTS

Subject	Trial	Steady State	Overall Average
C	1	111	112
	2	137	138
	3	111	110
	4	160	162
	5	127	124
	6	120	119
	7	98	97
	8	105	104
B	1	145	148
	2	124	126
	3	125	125
	4	146	150
	5	127	126
	6	137	139
	7	118	122
	8	120	121

TABLE 3

COST OF DONNING THE FULL PRESSURE SUIT IN A RESTRICTED SPACE

Donning Vol (cu ft)	Vol Ratio*	Av Heart Rate (beats/min)	Time (min)	Work Rate (kcal/min)	Work Rate per Kg. (kcal/min/kg)	Total Work per Kg. (kcal/kg)
SUBJECT B (78.0 kg)						
20.9	8.1	140	6.8	8.8	.113	.766
20.9	8.1	143	6.8	9.3	.119	.805
20.9	8.1	139	8.2	8.7	.112	.917
23.9	9.3	147	5.4	10.0	.128	.690
23.9	9.3	137	8.5	8.4	.107	.912
30.9	12.0	161	5.3	12.2	.156	.824
39.5	15.3	156	5.5	11.4	.146	.804
39.5	15.3	164	5.1	12.7	.162	.824
∞	∞	152	5.4	10.8	.138	.746
Mean & Std. Dev.		149±10	6.3±1.2	10.3±1.6	.131±.051	.810±.295
SUBJECT M (95.5 kg)						
23.9	7.6	141	14.9	14.2	.148	2.209
25.1	7.9	125	10.5	11.7	.122	1.281
30.9	9.8	137	10.2	13.5	.142	1.449
37.1	11.7	134	10.7	13.1	.137	1.465
Mean & Std. Dev.		134±6	11.4±2.0	13.0±1.0	.137±.080	1.6±.013
SUBJECT C (68.6 kg)						
16.6	7.3	130	9.1	7.6	.111	1.004
16.6	7.3	128	8.2	7.4	.110	0.879
17.2	7.6	125	6.6	7.0	.102	0.676
21.0	9.2	130	6.7	7.6	.111	0.799
21.0	9.2	120	7.3	6.5	.094	0.690
23.9	10.5	124	11.0	6.9	.101	1.103
23.9	10.5	129	7.8	7.5	.109	0.851
Mean & Std. Dev.		127±4	8.1±1.6	7.3±0.4	.105±.044	.849±.382

*Ratio of donning volume to subject volume (see text)

TABLE 4

COST OF DONNING THE FULL PRESSURE SUIT IN A GAS-TIGHT BAG

Trial	Time (min)	Total Work (kcal)	Work Rate (kcal/min)	Work Rate per kg (kcal/min/kg)	Total Work per kg (kcal/kg)
			SUBJECT C (68.6 kg)		
1	8.4	60	7.1	.103	.875
2	6.8	56	8.2	.120	.816
3	4.65	50	10.8	.157	.729
4*	9.5	85.8	9.0	.131	1.251
			SUBJECT CM (74.2 kg)		
5	5.05	67.8	13.4	.181	.914
6	6.5	64.8	10.0	.135	.874
7*	5.6	84	15.0	.202	1.134
MEAN (1,2,3, 5,6)	6.3	59.7	9.9	.139	.842
MEAN (4,7)	7.6	84.9	12.0	.167	1.193

*Subjects donned more tightly fitting suits

TABLE 5

COMPARISON OF TWO SIMULTANEOUS METHODS OF MEASURING COST OF DONNING THE FULL PRESSURE SUIT

SUBJECT C (68.6 kg)

Trial	Time (min)	Total Work (kcal)		Work Rate (kcal/min)		Work Rate per kg (kcal/min/kg)		Work Rate per kg (kcal/kg)	
		Ox*	HR**	Ox	HR	Ox	HR	Ox	HR
1	8.4	60	66	7.1	7.8	0.103	0.114	0.875	0.962
2	6.8	56	70.7	8.2	10.4	0.120	0.152	0.816	1.031
3	4.65	50	45	10.8	9.7	0.157	0.141	0.729	0.656
4	9.5	85.8	96	9.0	10.1	0.131	0.147	1.251	1.399
Mean	7.34	63.0	69.4	8.8	9.5	0.128	0.138	0.918	1.012

*Determination of energy expended by direct measurement of oxygen consumed

**Determination of energy expended by measurement of heart rate (based on this subject's calibration curve of heart rate vs. oxygen consumed)

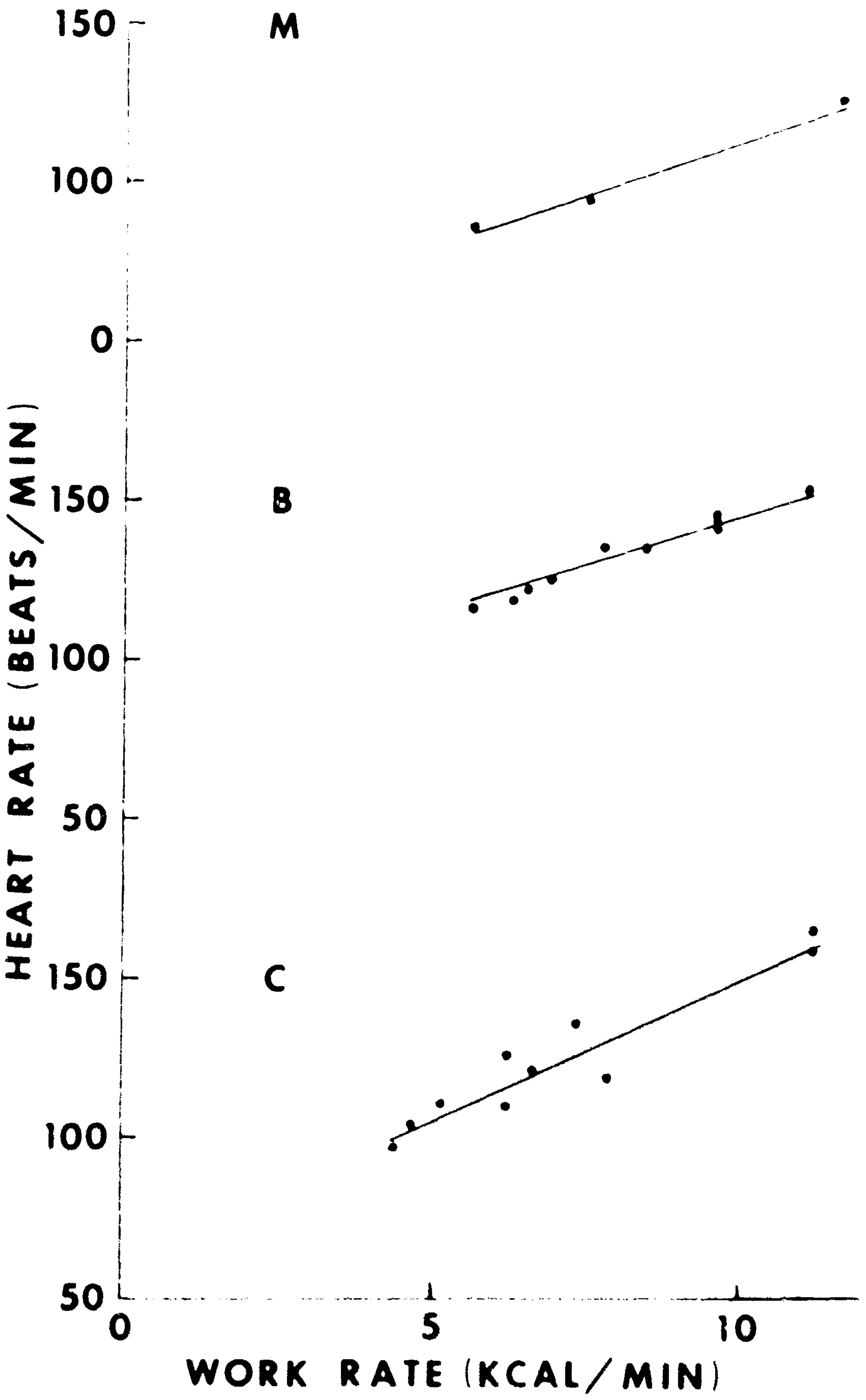

FIGURE 1

CALIBRATION CURVES OF HEART RATE VS. TREADMILL WORK RATE FOR THREE SUBJECTS

PHOTO NO: CAN-359715(L)-3-64

FIGURE 2

DONNING PROCEDURE FOR THE U.S. NAVY MK4 FULL PRESSURE SUIT

FIGURE 3

APPARATUS USED FOR ADJUSTING THE VOLUME
OF THE SUIT DONNING SPACE

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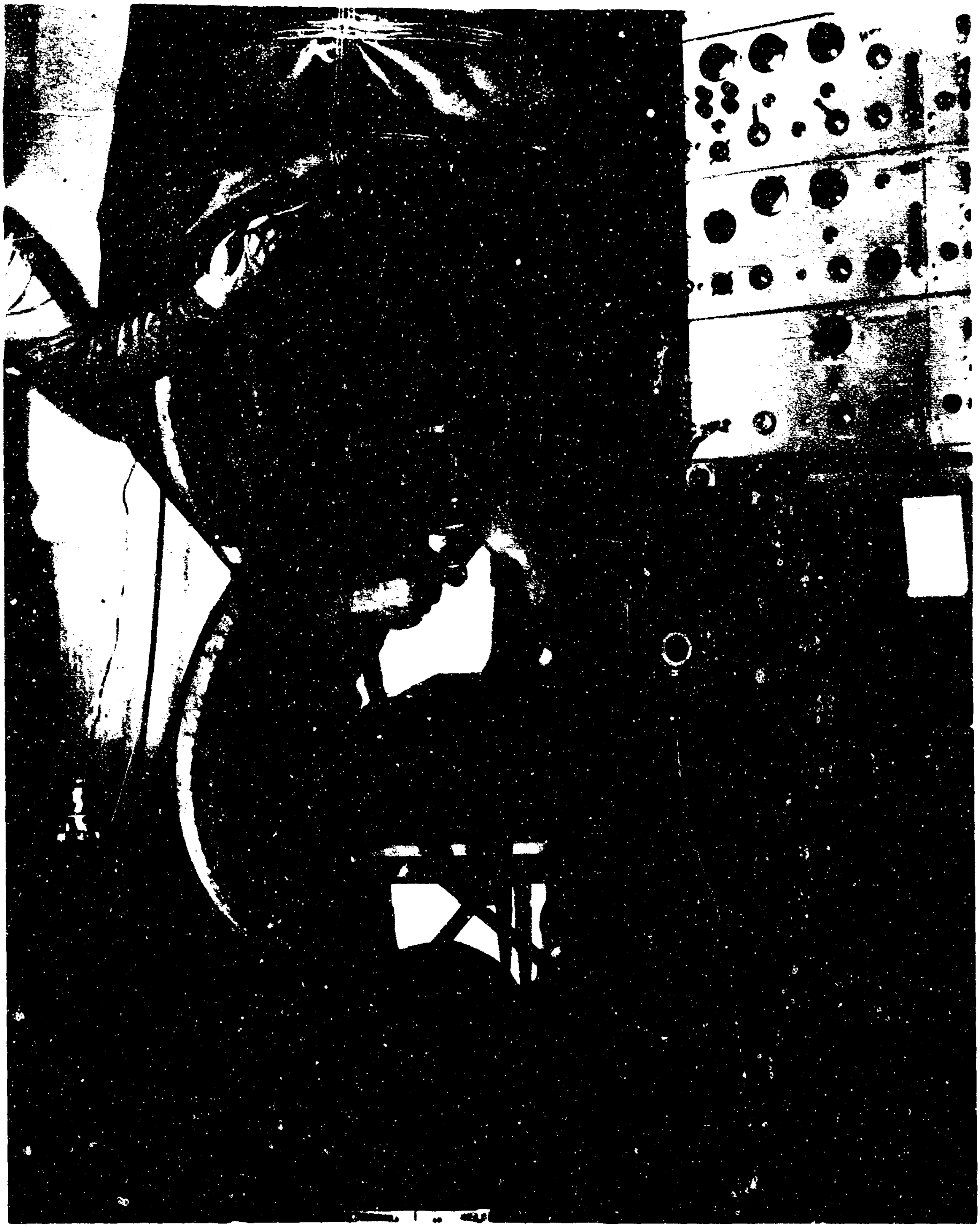

FIGURE 4

IMPERMEABLE BAG IN WHICH PHYSIOLOGICAL COST OF
SUIT DONNING PROCEDURE WAS DIRECTLY MEASURED

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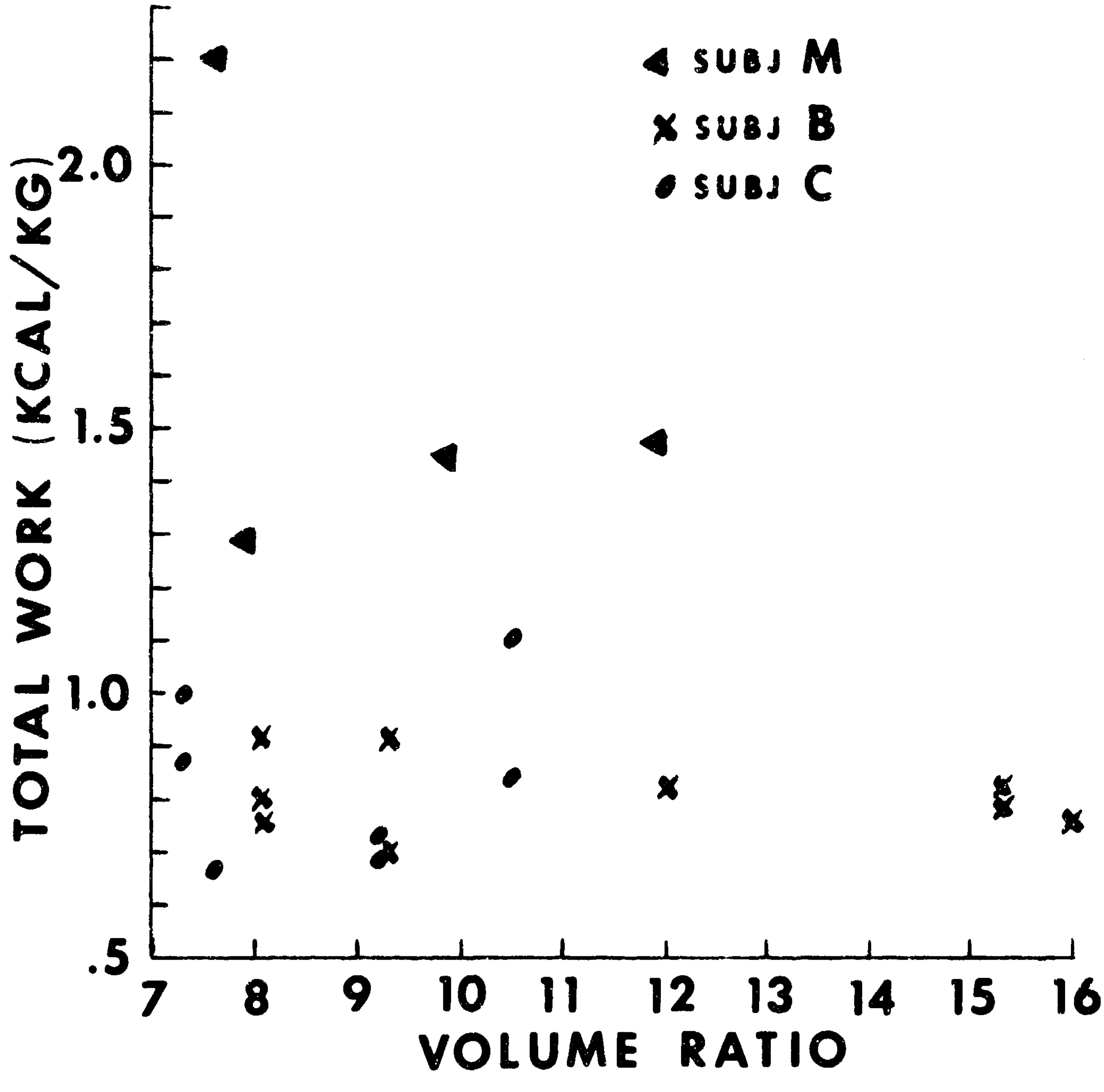

FIGURE 5

TOTAL WORK OF DONNING THE FULL PRESSURE SUIT
AS A FUNCTION OF VOLUME RATIO

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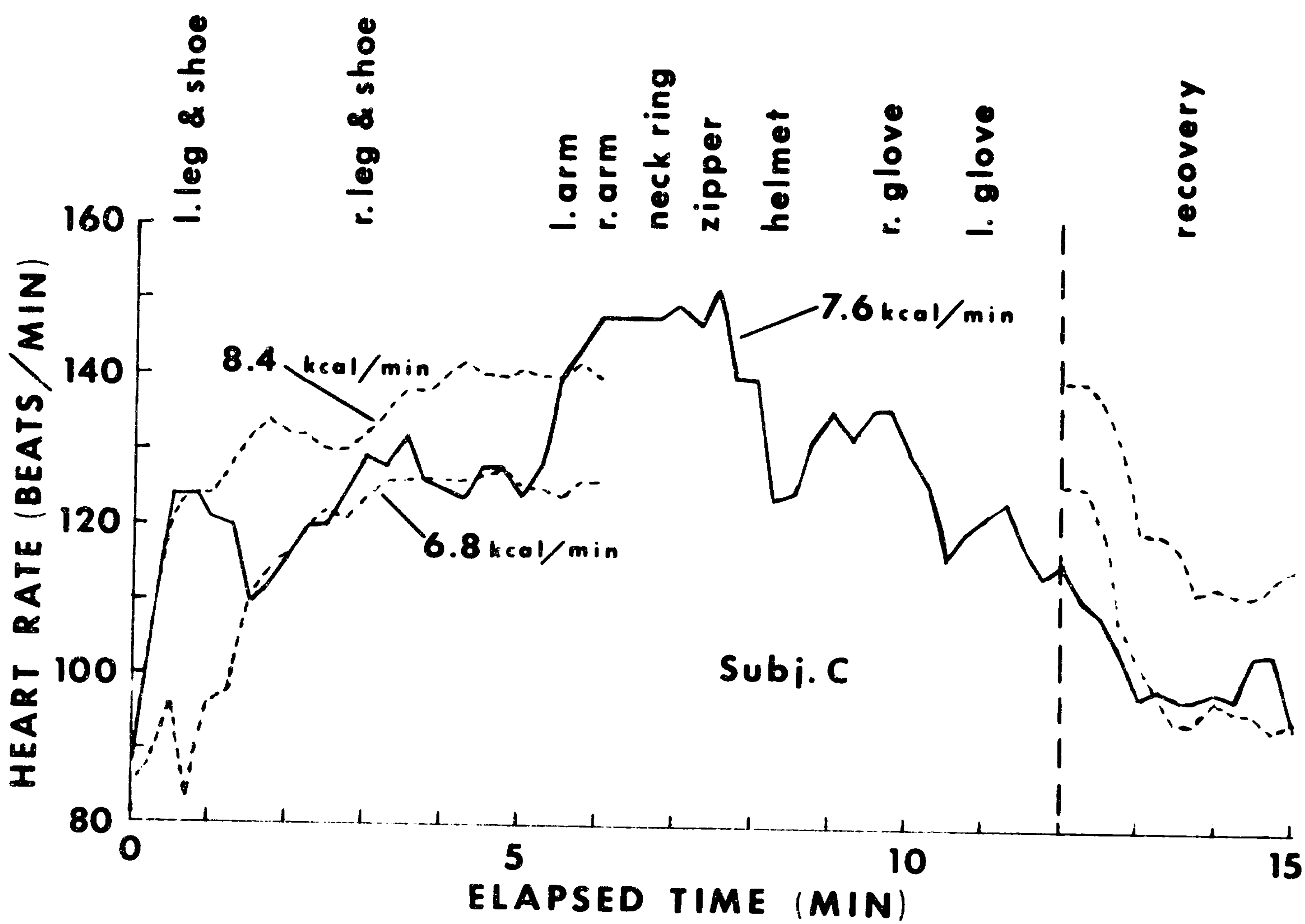

FIGURE 6

HEART RATE DURING TREADMILL AND SUIT DONNING WORK